

ABSTRACT

Understanding the mechanics of aerial cable installation is essential to the cable engineer for proper plant design and for maximum cable plant reliability and longevity. A key part of that understanding is the calculation of sags and tensions. Although basic sag and tension equations are available, little is available on calculating sag and tension with changing temperature and load.

This paper extends the basic sag and tension equations to address these effects, and gives the ability to solve integrally supported (Figure 8) cable, tightly lashed cable, and unequal elevation problems. The equations are applied to several basic tension and clearance requirements of the 1993 National Electrical Safety Code (NESC) which can only be addressed through calculation. They are also used to analyze expansion loop life, tight lashing, cable buckling, and center conductor pullouts. Obscure cable failure modes caused by wind gusting, solar heating and radiative cooling are discussed.

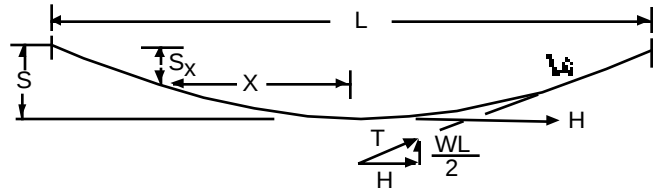
INTRODUCTION

The calculation of sag and tension can be quite useful to the cable television engineer. The calculations are used to select the appropriate size support strand for a given application or to determine if clearance requirements are met. With today's clearance requirements the only way to assure clearance requirements are met is by calculation. The calculations serve as an aid to the cable designers who determine the mechanical stress that the cable must be capable of withstanding or to evaluate such problems as expansion loop cracks and center conductor pullouts. The following is a discussion of sag and tension calculations which develops the simple case of a single wire suspended between two supports at equal elevation and works up through multiple elements, which takes into consideration each of the cable's components, with various loads and temperatures at unequal elevations.

BASIC EQUATIONS: WIRE, EQUAL EVALUATIONS

This first section covers the basic equations that apply. The sections that follow describe the application of these concepts. Figure 1 shows a single span of cable suspended between two fixed supports at equal elevations.

Figure 1.



$$H = \frac{WL^2}{8S} \quad (1)$$

$$L_c = L + \frac{8S^2}{3L} \quad (2)$$

Where:

H = Horizontal component of tension (pounds)

W = Linear weight of the wire (pounds/foot)

L = Distance between supports (feet)

S = Sag (feet)

L_c = Actual length of wire (feet)

These equations¹ are a parabolic approximation of the actual form that a flexible wire assumes, which is a catenary. The equation for a catenary is:

$$S = \left(\frac{H}{W} \right) \left[\cosh \left(\frac{WL}{2H} \right) - 1 \right] \quad (3)$$

$$\approx \frac{WL^2}{8S}$$

The difference between the catenary and the parabola is that the parabola is approximately 0.5 percent smaller if the sag is about 6 percent of the span. Generally, the sag is less than 2 percent for most cable television applications.

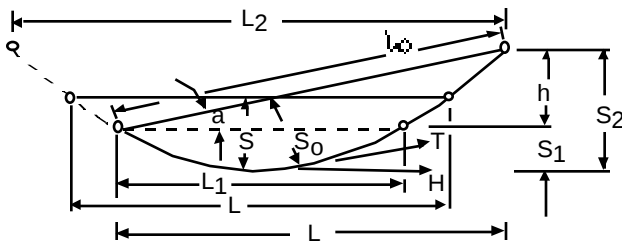
Another useful equation can be used to find the sag at any point along the span:

$$S_x = S \left(1 - \frac{4x^2}{L^2} \right) \quad (4)$$

UNEQUAL ELEVATIONS

The wire will assume the catenary form (or the parabolic approximation of this form) regardless of where the supports are located. The supports simply apply an equal and opposite vertical and horizontal force on the cable. Thus, the supports can be anywhere on the curve. Of course, after the load or temperature or both change, the sag changes. The supports are still on a parabola, but the parabola is different.

Figure 2.



$$S = S_0 = \frac{WL_0^2 \cos \alpha}{8T}$$

$$= \frac{WL^2}{8T \cos \alpha} = \frac{WL^2}{8H} \quad (5)$$

$$L_1 = L - \frac{2hH}{WL} \quad (6)$$

$$L_2 = L + \frac{2hH}{WL} \quad (7)$$

$$S_1 = \frac{WL_1^2}{8H} \quad (8)$$

$$S_2 = \frac{WL_2^2}{8H} \quad (9)$$

$$L_c = L + \left(\frac{4}{3} \right) \left[\left(\frac{S_1^2}{L_1} \right) + \left(\frac{S_2^2}{L_2} \right) \right] \quad (10)$$

Where:

T = Tension in the direction of the cable (pounds)

With these equations¹ (with Eqs. 6 and 7 slightly modified from the referenced source) the initial sag or tension can be calculated. Of course, one or the other must be known and span length and cable weight must also be given. They can be used, for instance, to calculate clearance over roads and sidewalks, and to determine specific size strand to be used under worst case loading. Note,

however, that there is no mention of the properties of the materials such as their thermal coefficient of linear expansion or their elastic modulus. Indeed, these equations are correct but only for the initial conditions.

TEMPERATURE AND LOAD CHANGES

There are other conditions which encompass a range of temperatures and loads. For example, what if the amount of installed sag is fixed at some maximum value, and then the span is subjected to a different temperature and a load which may exceed the strand's strength? Or, if the sag and tension is known for the worst case load, what would the stringing sag and tension be at a different temperature and load? To solve these types of problems, further knowledge of the materials that are used is needed and the above equations must be adapted.

Suppose the wire is installed at some initial temperature (T_0) and the cable has a linear weight (W_0). Then the temperature drops to some final temperature (T_f) and the linear weight of the cable changes to some final weight (W_f) because, perhaps, ice has accumulated and a strong wind is blowing. What happens to the sag and tension?

As the temperature drops, the cable tries to get shorter because of its expansion coefficient, but because the span length is fixed the sag must get smaller, thus increasing the tension. The tension also affects the length of the cable due to its elastic modulus. So, as the tension increases, the length of the cable increases thus minimizing the effect. On one hand the cable tries to get shorter because of temperature, but it cannot get as short as it would like because the tension is increasing. Finally, the increased load causes the tension to increase, but because the cable is elastic it elongates in its elastic region thus increasing the sag and reducing the tension. All of this occurs simultaneously, and a balance or equilibrium is continually being maintained.

To determine the final sag and tension a mathematical description of these events will be given.

Unstressed Length

The most important quantity in the process of determining the final sag and tension is the cable's initial unstressed length at the initial temperature. The cable's unstressed length is the length of the cable if it had no tension or stress on it. It should not be confused with L_c , the actual cable length.

The unstressed cable length is necessary to know because, as additional tension is applied to the cable, its

stressed length changes as a function of its unstressed length (and also its elastic modulus). To determine the appropriate amount of expansion and contraction due to temperature changes, again the unstressed length must be used (along with its thermal coefficient of linear expansion).

The stressed length of the cable (L_c) can be determined from Eq. 2 or 10. From this the unstressed length can be determined. Assuming that the material is elastic and follows Hooke's Law, its strain is proportional to the stress applied by a factor called the elastic modulus.

$$E = \frac{\sigma}{e} \quad (11)$$

$$= \frac{FL}{A \Delta L} \quad (12)$$

Where:

E = Modulus of elasticity (pounds/square inch)

e = Strain = $\Delta L/L$ (dimensionless)

σ = Stress = F/A (pounds/square inch)

ΔL = Change in length as the result stress (feet)

F = Force (pounds)

A = Cross sectional area perpendicular to the force applied (square inches)

$$L_c = L + \Delta L \quad (13)$$

$$= L + \frac{FL}{AE} \quad (14)$$

$$L_c = L \left(1 + \frac{F}{AE} \right) \quad (15)$$

It is assumed that the tension is the same along the entire length, but, because the wire has a finite weight per unit length, the ends of the wire near the support have more tension. The horizontal component of the tension is the same everywhere in the wire. The vertical component of the tension is zero at the lowest point since there is zero cable weight. The vertical component of tension at the support is the weight of the cable between the support and the lowest point.

The unstressed length, then is:

$$L_{u0} = \frac{L_c}{1 + \left(\frac{H}{AE} \right)} \quad (16)$$

It should be noted that this only applies for stresses within the elastic limit of the material. Also, the elastic modulus of the material is not necessarily constant with temperature; therefore, a knowledge of the characteristics of the materials is important.

TEMPERATURE CHANGES

Once the unstressed length has been determined at the initial temperature, the unstressed length can be determined at other temperatures from the following:

$$L_{uf} = L_{u0} [1 + a (T_f - T_0)] \quad (17)$$

Where:

L_{uf} = Final unstressed length at T_f (feet)

L_{u0} = Original unstressed length at T_0 (feet)

a = Thermal coefficient of linear expansion (inch/inch °F)

T_f = Final temperature (°F)

T_0 = Original temperature (°F)

It should be noted that the thermal coefficient is not necessarily constant and again it is necessary to be familiar with the properties of the materials.

Most materials have positive thermal coefficients of linear expansion which cause them to get longer when the temperature increases. When the temperature decreases, they get shorter. (In some cases, materials are specially selected because they have negative expansion coefficients so that when used in conjunction with other materials the overall change in length is minimized or matched to some other component such as in fiber optic transmission lines.)

There are several factors that affect temperature. The temperature of the cable or wire is of course affected by the air temperature. The air temperature changes on a daily basis (diurnal) as well as yearly basis (annual). If electrical current is carried through the wire, a tempera-

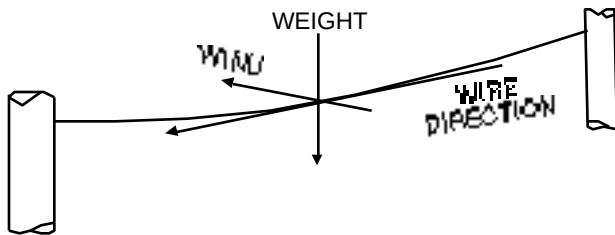
ture rise will also occur, but, generally speaking, this rise is small for CATV cable. Another factor is radiation. During the day the cable is heated from the sun. At night the cable radiates its heat toward clear skies. The wind tends to minimize this effect.

Measurements made in Connecticut on the longest day of the year when the sun's rays are most direct indicate that a temperature rise of about 45°F above ambient can be expected on black jacketed cable and about 24°F rise above ambient for unjacketed aluminum sheathed coaxial cable. At night, in the same area, the temperature of black jacketed cable was about 8°F below ambient and 4°F below ambient for unjacketed aluminum cable.

LOAD CALCULATIONS

Before the final sag and tension can be calculated, it is necessary to evaluate the span of wire in terms of load. Initially we assumed that the wire's weight was the only load applied. Under worst case conditions, the wire may have ice formed around its circumference and at the same time a strong wind blowing on it. The total load on the wire is the resultant of all vertical and horizontal loads. (The horizontal load here is perpendicular to both the vertical and the wire itself.)

Figure 3.



The total resultant load of the wire is the vector sum of all the horizontal and vertical components:

$$W_f = [(\Sigma W_v)^2 + (\Sigma W_h)^2]^{1/2} \quad (18)$$

Where:

- W_f = Final linear cable weight (pounds/foot)
- ΣW_v = Sum of all vertical weights (pounds/foot)
- ΣW_h = Sum of all horizontal forces (pounds/foot)

As an example, the vertical weight components may include: the weight of the support strand, the weight of all the cables, the weight of the lashing and possibly a cylinder of ice around the group. The horizontal force is only attributed to wind loading. In some cases a weight constant (e.g., in heavy loading districts, 0.3 pound/foot) is added to the resultant final weight for safety.

Ice Loading

The additional weight caused by ice build-up on the cable is usually calculated based on a hollow cylinder having an inside diameter equal to the outside diameter of the bundle of the cables and the support strand and with a given thickness which is usually 0.25 inches or 0.5 inches depending on which loading district is used. Using 57 pounds per cubic foot as the weight of ice³, the linear ice weight around the cable can be calculated from:

$$W_{ice} = 1.244 (D_i t + t^2) \quad (19)$$

Where:

- W_{ice} = Linear ice weight (pounds/foot)
- D_i = Diameter over cable bundle (inches)
- t = Thickness of the ice (inches)

Wind Loading

The wind loading on a circular surface can be calculated from³:

$$P = 0.00256V^2 \quad (20)$$

Where:

- P = Horizontal wind pressure (pounds/square foot)
- V = Wind velocity (miles/hour)

In order to use this equation, the pressure must be converted to a load or force on the projected surface of the bundle that faces the wind. Assuming that the wind is perpendicular to the cable and we wish the results to be in terms of pounds/foot:

$$F_{wind} = \frac{PD_0}{12} \quad (21)$$

Where:

- F_{wind} = Wind loading (pounds/square foot)
- P = Wind pressure (pounds/square foot)
- D_0 = Diameter of cable bundle (inches)
[including ice if appropriate]

It should also be pointed out that horizontal loading results in sags which are not vertically directed. The horizontal and vertical components of the final sag can be resolved since they are proportional to the horizontal and vertical loads described in Eq. 18, i.e.,

$$S_f = (S_v^2 + S_h^2)^{1/2} \quad (22)$$

So, for example the actual vertical component of the sag would be:

$$S_v = \frac{S_f (\Sigma W_v)^2}{(\Sigma W_v)^2 + (\Sigma W_h)^2} \quad (23)$$

FINAL SAG AND TENSION

From Eq. 17 the final unstressed length of the wire can be determined based on the final temperature. From Eq. 15 we can determine the actual length of the wire if its tension is known:

$$L_{cf} = L_{uf} \left(1 + \frac{H_f}{AE} \right) \quad (24)$$

Where:

L_{cf} = Final stressed length of the wire (feet)

L_{uf} = Final unstressed length of the wire (feet)

H_f = Final horizontal tension (pounds)

A = Cross sectional area of the wire (square inches)

E = Elastic modulus, tensile (pounds/square inches)

If the supports are at equal elevations, the final length of the wire is also (from Eq. 2):

$$L_{cf} = L + \frac{8S_f^2}{3L} \quad (25)$$

Where:

S_f = Final sag (feet)

This is actually a special case of supports at unequal elevations. The following progression puts Eq. 10 into the same form as Eq. 25. Consider:

$$L_c = L + \left(\frac{4}{3} \right) \left[\left(\frac{S_1^2}{L_1} \right) + \left(\frac{S_2^2}{L_2} \right) \right] \quad (26)$$

From Eqs. 5, 6, and 7, S_1 and S_2 can be set in terms of S as:

$$S_1 = \frac{SL_1^2}{L^2} \quad (27)$$

$$S_2 = \frac{SL_2^2}{L^2} \quad (28)$$

So Eq. 26 can be transformed to:

$$L_c = L + \left(\frac{4S^2}{3L^4} \right) (L_1^3 + L_2^3) \quad (29)$$

From Eqs. 8 and 9, L_1 and L_2 can be stated in terms of S and h and L as:

$$L_1 = L \left(1 - \frac{h}{4S} \right) \quad (30)$$

$$L_2 = L \left(1 + \frac{h}{4S} \right) \quad (31)$$

After a bit of work we find:

$$L_1^3 + L_2^3 = L^3 \left(2 + \frac{3h^2}{8S^2} \right) \quad (32)$$

which can be plugged into Eq. 29 to yield:

$$L_{cf} = L + \left(\frac{8S_f^2}{3L} \right) \left(\frac{h^2}{2L} \right)$$

Back to the problem at hand, we were in search of another equation to set equal to Eq. 24; our search is over with Eq. 33. Actually Eq. 24 would be better in terms of S_f , like Eq. 33. This is easily done via Eq. 1.

$$L_{cf} = L_{uf} \left[1 + \left(\frac{W_f L^2}{8S_f AE} \right) \right] \quad (34)$$

Setting Eq. 33 and 34 equal to each other yields:

$$L + \left(\frac{8S_f^2}{3L} \right) + \left(\frac{h^2}{2L} \right) - L_{uf} - \left(\frac{L_{uf}W_fL^2}{8S_fAE} \right) = 0 \quad (35)$$

Which can be put into the form of:

$$S_f^3 + S_f \left(\frac{3L}{8} \right) \left(L + \frac{h^2}{2L} - L_{uf} \right) - \left(\frac{3L}{8} \right) \left(\frac{L_{uf}W_fL^2}{8AE} \right) = 0 \quad (36)$$

Notice that every variable in Eq. 36 is defined except the final sag (S_f). This equation takes into account a new temperature and a new load. S_f can be found via the solution of the cubic equation. Eq. 36 can be rewritten as:

$$S_f^3 + aS_f + b = 0 \quad (37)$$

Where:

$$a = \frac{3 \left[L^2 + \left(\frac{h^2}{2} \right) - LL_{uf} \right]}{8} \quad (38)$$

$$b = \frac{-3W_fL^3L_{uf}}{64AE} \quad (39)$$

The solution of this particular form of cubic equation is as follows⁴:

$$\text{If } \left(\frac{a}{3} \right)^3 + \left(\frac{-b}{2} \right)^2 \geq 0 \quad (40)$$

Then

$$S_f = \left\{ \left(\frac{-b}{2} \right) + \left[\left(\frac{a}{3} \right)^3 + \left(\frac{-b}{2} \right)^2 \right]^{1/2} \right\}^{1/3} + \left\{ \left(\frac{-b}{2} \right) - \left[\left(\frac{a}{3} \right)^3 + \left(\frac{-b}{2} \right)^2 \right]^{1/2} \right\}^{1/3} \quad (41)$$

Note, if the above condition is met and since $-b/2$ is always positive, the result will always be a real root.

$$\text{If } \left(\frac{a}{3} \right)^3 + \left(\frac{-b}{2} \right)^2 < 0 \quad (42)$$

Then

$$S_f = 2 \left(\frac{-a}{3} \right)^{1/2} \cos \left\{ \left(\frac{1}{3} \right) \cos^{-1} \left[\frac{\left(\frac{-b}{2} \right)}{\left(\frac{-a}{3} \right)^{3/2}} \right] \right\} \quad (43)$$

Note, if Eq. 42 is true and since $(-b/2)$ is always positive then $(a/3)$ is certainly negative and again a real root will be obtained.

Once the final sag is found the final tension is easily found from:

$$H_f = \frac{W_fL^2}{8S_f} \quad (44)$$

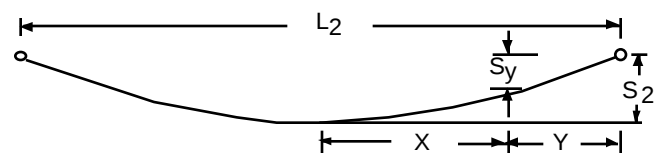
CLEARANCE CALCULATIONS

Sometimes when checking to assure that the proper clearances are met (e.g., during make ready), it is necessary to know the elevation of the wire at points other than at the lowest point. For equal elevations Eq. 4 can be used. The sag at any point is given with respect to the lowest point which, for problems of equal elevation, is always exactly half-way between the supports.

For problems of unequal elevation, it is not particularly helpful to know what the sag is with respect to the position of the lowest point sag because not only is the lowest point sag not exactly half-way between the two supports, it may not be (mathematically) between the two supports at all!

Equation 4, however, can be adapted.

Figure 4.



From the above figure (which is simply Fig. 2 without some of the details, but includes some new information about the sag at any point) it can be seen that x can be stated in terms of y , which is the horizontal distance from the highest support as:

$$x = \left(\frac{L_2}{2} \right) - y \quad (45)$$

Where:

- x = Distance from the lowest point (feet)
- y = Distance from the highest point (feet)
- L_2 = Span length (feet)
- S_2 = Sag at lowest point (feet)

Substitution Eq. 45 into Eq. 4 we obtain:

$$S_y = S_2 \left\{ 1 - \frac{4 \left[\left(\frac{L_2}{2} \right) - y \right]^2}{L_2^2} \right\} \quad (46)$$

Where:

S_y = Sag at y from the highest support (feet)

Equation 46 can also be used for equal elevation problems. Notice from Eq. 9 that L_2 is not fixed. L_2 will be different from its original value depending upon the tension (H). Therefore, it is necessary to determine both the final L_2 and S_2 if clearance is to be calculated.

Creep

It should be noted that materials, when exposed to stress even if below their elastic limit for a long period of time, tend to deform and take a permanent set. This slow acting deformation is called creep. For clearance calculations that require exacting accuracy, factors such as creep must be taken into consideration and creep data on the material used to support the cable should be obtained. Although it is beyond the scope of this paper to provide such information, two data points are given for discussion. The creep rate on extra high strength galvanized steel wire and strand is about 0.08 percent at 70 percent of the wire's rated breaking load. This much creep can occur in 24 hours, but very little additional creep takes place over the next 1000 hours of exposure, perhaps an overall total of 0.09 percent.

To illustrate the implications of this "small" number, consider a 100 foot span with 1 foot of sag. Suppose

during the course of time the strand is exposed to such stress that would cause 0.09 percent creep. The implication can be approximated from Eq. 2. The resulting sag would be 2.09 feet instead of returning to 1 foot as might be expected. Although the strand should not be exposed to such stresses, the purpose of this illustration is to show the limitations of the calculations and highlight the need for caution and good engineering judgement.

SPECIAL CONFIGURATIONS

Multiple Elements

In some cases the wire may be comprised of several different materials with different cross sections. Cable with integral messengers ("Figure 8") and drop cable are examples. Each material has its own expansion coefficient and elastic modulus. When suspended, each element takes a different portion of the total load. The amount of the load that any particular cable element takes is a function of its elastic modulus and area as compared to the total resultant modulus of all the materials and the total area of all the materials.

The resultant modulus can be found by multiplying the modulus of each material by the ratio of the material's area to the total area:

$$E_r = \left(\frac{A_1}{A_T} \right) E_1 + \left(\frac{A_2}{A_T} \right) E_2 + \left(\frac{A_3}{A_T} \right) E_3 + \dots + \left(\frac{A_n}{A_T} \right) E_n \quad (47)$$

Where:

- E_r = Resultant elastic modulus (pounds/square inch)
- A_T = Total cross sectional area of the wire (square inches)
- A_1 = Cross sectional area of element 1 (square inch)
- A_2 = Cross sectional area of element 2 (square inch)
- A_3 = Cross sectional area of element 3 (square inch)
- A_n = Cross sectional area of element n (square inch)
- E_1 = Elastic modulus of element 1 (pounds/square inch)
- E_2 = Elastic modulus of element 2 (pounds/square inch)
- E_3 = Elastic modulus of element 3 (pounds/square inch)
- E_n = Elastic modulus of element n (pounds/square inch)

These values (i.e., E_r and A_T) along with the following value for expansion coefficient can be directly substituted into the above equations for sag and tension wherever E , A , and a occur.

The resultant coefficient of linear expansion (a_r) is calculated as follows:

$$a_r = \frac{(A_1 E_1 a_1 + A_2 E_2 a_2 + \dots + A_n E_n a_n)}{(A_1 E_1 + A_2 E_2 + \dots + A_n E_n)} \quad (48)$$

By using these values for E_r , A_r , and a_r the final sag and final tension can be determined at the new temperature with the new load.

Because the above equations which include elastic modulus only work when the materials are stressed within their elastic region, it is important to make sure that each element's elastic limit is not exceeded.

The unstressed length of all the elements is the same only at the original temperature. It is assumed that any stress built into the cable is small compared to the installed stress. Once the temperature changes, each element expands and contracts at its own rate. Also, each element has its own elastic modulus and cross sectional area. Unless the elements are bonded together in some fashion they may move independently of one another.

In order to determine the stress on any particular element, the unstressed final length must first be determined. It can be calculated, based on the change in temperature and the expansion coefficient of the element in question, as follows:

$$L_{ufn} = L_{uon} [1 + a_n (T_f - T_o)] \quad (49)$$

Where:

L_{ufn} = Final unstressed length of any particular element n (feet)

L_{uon} = Original unstressed length of any particular element n (feet)

a_n = thermal coefficient of linear expansion of any particular element n (inch/inch / °F)

Note: L_{uon} is the same for all elements and exactly the same as that given in Eq. 16.

The final cable length (under stress) is the same for all elements. It can be determined from either Eq. 2 or Eq. 10. The strain that the cable element is under is then:

$$e_n = \frac{L_{cf} - L_{ufn}}{L_{ufn}} \quad (50)$$

The stress is the modulus times the strain:

$$\sigma_n = \frac{E_n (L_{cf} - L_{ufn})}{L_{ufn}} \quad (51)$$

And the tension on element n is:

$$H_n = \frac{A_n E_n (L_{cf} - L_{ufn})}{L_{ufn}} \quad (52)$$

Where:

H_n = Tension on element n (pounds)

A_n = Cross sectional area of element n (square inches)

E_n = Elastic modulus of element n (pounds/square inch)

L_{cf} = Final cable length (feet)

L_{ufn} = Unstressed final length of element n (feet)

The stress in Eq. 51 should be tested to assure that the elastic limit not be exceeded. Aside from exceeding the elastic limit of any particular element, one additional caution should be noted. Generally, "Figure 8" cable used in CATV applications is for distribution purposes and so taps are installed. To install a tap the cable must be cut and separated from the messenger wire. Cutting the cable relieves the stress in the cable at the point where it is cut. This tension, however, does not necessarily disappear. A significant portion, if not all of it, is diverted to the steel messenger wire. So, wherever taps are installed in messenger cable, you must assure that the total tension does not exceed the safe limits of the messenger as if it were alone.

Cable Tightly Lashed

In cases where cable is lashed to the strand so tight as to restrict cable from moving independently of the steel strand support, a similar analysis can be performed. This condition can occur even if the lashing is not restrictive: by having no expansion loops.

We will call this third case "cable restrained". In this case, the steel strand is installed and loaded with the cable. The cable is then lashed so tight that cable movement is restricted. The resultant condition is that the steel strand is under stress and the cable has zero stress.

After the temperature, load or both change, the load is not distributed like it was in the case of "Figure 8" cable. They differ in that there is no original cable tension; so the original unstressed cable length is the same as the actual cable length (L_{co}). The original unstressed steel length is slightly shorter.

It will be assumed that the cable and steel support strand are bound together, either by tight lashing or lack of expansion loops. This may not be the case, because some slightly differential movement between the cable and support strand can be expected, but it will allow us to evaluate the extreme conditions; the actual lying somewhere between this and the first case⁵ (i.e., the steel taking the full load at all temperatures and under loading conditions).

The first step in solving this problem is to find the unstressed length of the composite assembly. It is certainly not the unstressed strand length because the two components, the steel and the cable, are bound together. Nor is it the unstressed cable length. The unstressed length of the composite is somewhere between the two.

When the composite assembly is unstressed, an interesting condition occurs: the steel is under tension and the cable under compression.

Again, as before, the actual length of the assembly initially is found from Eq. 2.

$$L_c = L + \frac{8S^2}{3L} \quad (2)$$

The unstressed length can be calculated from:

$$L_u = \frac{L_c}{1 + \left(\frac{H}{A_T E_r} \right)} \quad (53)$$

E_r is found in the same way as for Figure 8 cable, Eq. 47. The tension, H , in Eq. 53 is the tension of the steel support alone. The original unstressed length can be used to find the final unstressed length at the final temperature from Eq. 17 except that the resultant expansion coefficient (a_r) should be used in place of a . Finally, the final sag can be calculated from Eq. 41 or 43. The total tension on the assembly can then be found from Eq. 44.

The original tension on the components was easily determined; the steel had all the tension, the cable had none. At final state, that is, after the load, temperature or both change, the tension on each component may not be quite so easy to determine. We will divide the tensions into two groups: namely, the tension on the steel and the tension on the other components.

To analyze the final tension on the steel, we must first determine its initial unstressed length. It is:

$$L_{uo\ steel} = \frac{L_{c\ o}}{1 + \left(\frac{H_o}{A_{steel} E_{steel}} \right)} \quad (54)$$

Changing the temperature altered this length to:

$$L_{uf\ steel} = L_{uo\ steel} [1 + a_{steel} (T_f - T_o)] \quad (55)$$

The stress on the steel is then:

$$\sigma_{steel} = \frac{E_{steel} (L_{cf} - L_{uf\ steel})}{L_{uf\ steel}} \quad (56)$$

The tension on the steel is:

$$H_{f\ steel} = A_{steel} \sigma_{steel} \quad (57)$$

The stress and tension on the other elements can be found in a similar manner except that the original unstressed cable length equals the original actual cable length.

$$L_{co} = L_{cuo} \quad (58)$$

The change in length of any particular element other than the steel can be determined from:

$$L_{ufn} = L_{co} [1 + a_n (T_f - T_o)] \quad (59)$$

Where the subscript "n" refers to one of the cable elements.

The stress on that particular element is then:

$$\sigma_n = \frac{E_n (L_{cf} - L_{ufn})}{L_{ufn}} \quad (60)$$

And the tension on that element is:

$$H_{fn} = A_n \sigma_n \quad (61)$$

Unfortunately, it is difficult to first assume full load at the lowest temperature for restrained cable. For example, you may want the tension on the strand to be 60 percent of its breaking strength at full load at the lowest temperature. The tension on the other components can be anywhere between zero and the material's elastic limit, depending on the original temperature.

In the other two cases, the original temperature and load have no restrictions. But in this case, cable restrained, the original conditions must be at the temperature at which the cable was lashed to the strand. Of course, if enough information is known about the final conditions, the initial conditions can be determined.

In review, three basic configurations have been discussed with regard to sag and tension. The first was a simple case of a single wire. The second considered multiple elements which can be applied to "Figure 8" type cable or drop wire. The last, "cable restrained", addressed what happens when the cable has zero tension initially but supports some of the load as conditions change. Each configuration was considered after the temperature, load or both changed.

APPLICATIONS

Strand Tension Under Worst Case Load

To illustrate the application of these equations a few examples will be given. Consider, first, a 125 foot span having a 500 and 750 size jacketed cables supported by a 0.25 inch EHS strand. Assume that the cable has expansion loops and is free to move independently of the steel support strand so that there is no tension on the cable under any condition. The cable was installed at 60°F and has a 1.5 percent sag (1.875 feet). The cable is installed in a heavy loading district with extreme wind loading of 21 pounds/square foot. The question is, what is the tension on the strand under worst case conditions?

From Table 1 and 3, the total weight of the strand, plus the 500J, plus the 750J, plus the double lashing is 0.439 pound/foot. The maximum tension on the strand must not exceed 60 percent of its rated break strength under worse case expected loading. The initial strand tension and cable length at 60°F can be calculated from Equations 1 and 2.

$$H = \frac{(0.439 \text{ pound/foot}) (125 \text{ feet})^2}{8 (1.875 \text{ feet})}$$

$$= 457.3 \text{ pounds}$$

$$L_c = 125 \text{ feet} + \frac{8 (1.875 \text{ feet})^2}{3 (125 \text{ feet})}$$

$$= 125.075 \text{ feet}$$

The unstressed length of the steel support strand is found from Eq. 16 and the elastic modulus of the strand from Table 2 and 3.

$$L_u = \frac{125.075}{1 + \left(\frac{457.3}{(0.035 \text{ 185}) (28 \times 10^6)} \right)}$$

$$= 125.016 \text{ 97 feet}$$

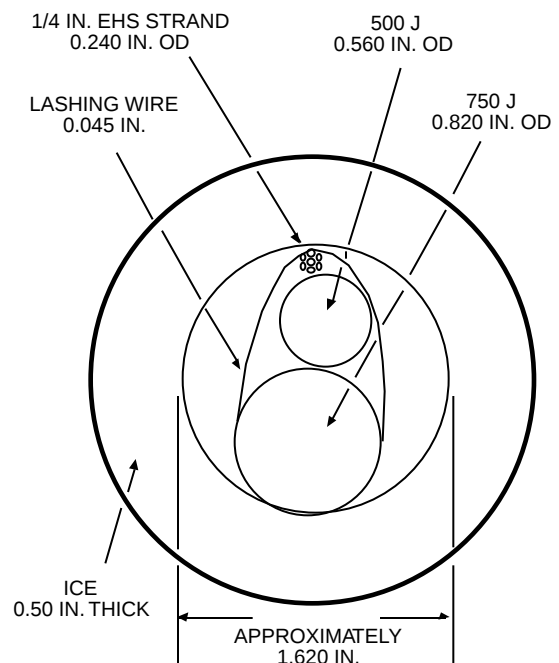
Now the unstressed length at any other temperature can be determined. From Table 4, the temperature for a heavy loading district is 0°F. From Eq. 17 and the expansion coefficient of steel in Table 2, the unstressed length of the steel at 0°F is:

$$L_{uf} = (125.016 \text{ 97}) [1 + 7.2 \times 10^{-6} (0 - 60)]$$

$$= 124.962 \text{ 96 feet}$$

Assuming that the cables are stacked one on top of the other and from the dimensions in Tables 1 and 3, the width of the cable plus the strand is 1.620 inches. From Eq. 19, 0.5 inch thick ice over the cable weighs 1.319 pound/foot. So the total vertical weight (i.e., ice plus the cable) is 1.757 pound per foot. See Figure 5.

Figure 5.



The horizontal load from the wind is calculated from Eq. 22. The projected diameter over the ice is 2.620 inches (i.e., 2 x 0.5 inch + 1.620 inches). The wind pressure for a heavy loading district, from Table 4, is 4 pounds/square foot. The loading is then:

$$F_{\text{wind}} = \frac{(4)(2.620)}{12}$$

$$= 0.873 \text{ pound/foot}$$

The vector sum of the horizontal and vertical loads calculated from Eq. 18 is:

$$W = [(1.757)^2 + (0.873)^2]^{1/2}$$

$$= 1.963 \text{ pounds/foot}$$

The weight added for a heavy loading district is 0.30 pounds/foot and results in a final weight of:

$$W_f = 1.963 + 0.30$$

$$= 2.263 \text{ pounds/foot}$$

To solve for the final sag in Eq. 37, a and b are first found from Eq. 38 and 39. The difference in support elevations, h, is zero so:

$$a = \frac{3[(125)^2 - (125)(124.96296)]}{8}$$

$$= 1.73608875$$

$$b = \frac{-3(2.263)(125)^3(124.96296)}{64(0.035185)(28 \times 10^6)}$$

$$= -26.27575$$

$$\left(\frac{a}{3}\right)^3 = 0.19380$$

$$\left(\frac{-b}{2}\right)^2 = 172.604$$

Clearly, Eq. 40 is true and the final sag (which is not vertically directed) can be found from Eq. 41 and the final tension from Eq. 1.

$$S_f = 2.779 \text{ feet}$$

$$H = \frac{(2.263)(125)^2}{8(2.779)}$$

$$= 1590 \text{ pounds}$$

This is the tension (horizontally directed) in the strand under heavy loading conditions. This is well within the 3990 pound maximum limit.

One more check is necessary and that is under extreme wind loading at 60°F. From Figure A2 the wind loading is 21 pounds/square foot. The resulting wind load from Eq. 22 is:

$$F_{\text{wind}} = \frac{(21)(1.620)}{12}$$

$$= 2.835 \text{ pounds/foot}$$

By adding the horizontal and vertical load components, the final load is 2.869 pounds/foot. Using the unstressed length at 60°F:

$$\left(\frac{a}{3}\right)^3 = -0.0186452$$

$$\left(\frac{-b}{2}\right)^2 = 277.746$$

The final sag and tension is found in the same way as before.

$$S_f = 3.30 \text{ feet}$$

$$H = 1698 \text{ pounds}$$

So the strand tension under extreme wind loading is well under the 3990 pound limit.

The above example was carried out in several steps:

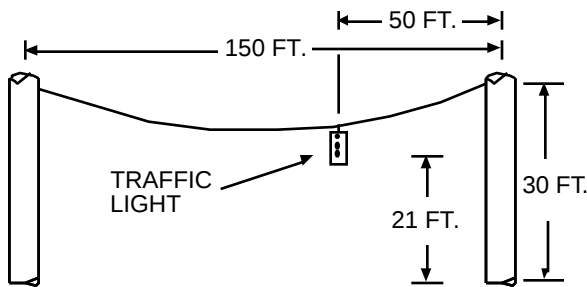
1. Calculate the initial tension from Eq. 1.
2. Calculate the initial cable length from Eq. 2.
3. Calculate the initial unstressed cable length from Eq. 16.
4. Calculate the final unstressed cable length from Eq. 17.
5. Calculate the final load from the loading tables and Eqs. 18 and 19.
6. Calculate the final sag from either Eq. 41 or 43.
7. Calculate the final tension from Eq. 44.

For unequal elevations problems, L_C is calculated from Eq. 10 and h is used in Eq. 38. These equations can be loaded into a computer or programmable calculator for easy calculations.

Clearance Over a Traffic Light

Consider, next, a situation where you wish to keep a 30 inch clearance, under all expected conditions, over a traffic light. If the steel support is installed so that it is loaded to about 5 percent of its rated strength will the proper clearances be met? Figure 6 shows a sketch of the span.

Figure 6.



The following information is available.

Support Strand:

- 0.25 inch EHS
- $E = 28 \times 10^6$ pounds per square inch
- $A = 0.035$ 185 square inches
- $a = 7.2 \times 10^{-6}$ inch/inch $^{\circ}\text{F}$

Cable:

- 1 - 750J
- 1 - 500J
- Double Lashed
- Diameter = 1.620 inches
- Weight = 0.439 pounds/foot

The cable is installed in a heavy loading district with 16 pounds/square foot extreme wind.

The initial (loaded) conditions from Eq. 1, 2, 16 and 46 are:

- $H = 330$ pounds
- $L_u = 150.198$ 554 feet
- $S = 3.74$ feet
- $S_y = 3.33$ feet at 50 feet from the support.

Assuming that the worst case is at 32°F with 0.5 inch ice, no wind and a 0.3 pound/foot weight constant, the following results are obtained:

- $W_f = 2.057$ 6 pounds/foot
- $L_{uf} = 150.168$ 274 feet
- $H_f = 1280$ pounds
- $S_y = 4.02$ feet
- $S_f = 4.52$ feet

Assuming Heavy Load Conditions:

- $W_f = 2.263$ pounds/foot
- $H_f = 1431$ pounds
- $S_f = 4.45$ feet

Assuming 120°F with no load:

- $W_f = 0.439$ pound/foot
- $H_f = 296$ pounds
- $S_f = 4.17$ feet

For heavy loading, 1431 pounds is about 22 percent of the strand's rated strength of 6650 pounds. The expected creep is approximately 0.015 percent. Doubling it for margin, 0.03 percent,

- $L_{cf} = 150.363$ 381 feet

This is a first order approximation of the increased sag over time due to creep. The sag in the middle of the span would be about 4.783 feet instead of 4.52 feet. As long as the attachments are: $21 + 2.5 + 5 = 28.5$ feet high, there should not be any clearance problem.

Tension on Composite Materials

Consider a 150 foot span at 60°F with 0.5 percent sag (0.75 foot). In this example let us assume that a single 750 non-jacketed cable is either tightly lashed to the strand or has no expansion loops so that it can not move independently of the 0.25 inch EHS support strand.

- $L = 150$ feet
- $S = 0.75$ feet
- $W = 0.299$ pounds/foot

Component	Material	A (square inch)	E (pounds/square inch)	a (inches/inches °F)
Strand	Steel	0.035 185	28.0×10^6	7.2×10^{-6}
Shield	Al	0.080 75	10.0×10^6	12.7×10^{-6}
Dielectric	T10 Foam	0.339 65	42.0×10^3	48.0×10^{-6}
Center	CuCladAl	0.021 38	10.6×10^6	12.2×10^{-6}
Resultant		0.476 965	4.26×10^6	10.4×10^{-6}

The resultant is calculated from Eqs. 47 & 48. The conditions at 60°F are:

$$S = 0.75 \text{ feet}$$

$$H_{\text{steel}} = 1,121 \text{ pounds}$$

$$H_{\text{total}} = 1,121 \text{ pounds}$$

$$H_{\text{alum}} = 0 \text{ pounds}$$

Assume the temperature drops to -40°F.

$$S_f = 0.27 \text{ feet}$$

$$H_{\text{total}} = 3,129 \text{ pounds}$$

	E (pounds)	Tension	Stress (pounds/ square inch)
$H_{\text{Steel}} =$	1,775	Eq. 57	50,448
$H_{\text{Shield}} =$	980	Eq. 61	12,136
$H_{\text{Diel}} =$	111	Eq. 61	327
$H_{\text{Center}} =$	264	Eq. 61	12,348

The stresses on the shield and center conductor have exceeded their elastic limits. This translates to excessive stress on the conductors. This span will be prone to center conductor pullout problems and stress fatigue.

Now assume instead that the cable was installed on a cold day, say at 40°F, and during the summer the cable temperature rose to 120°F. The initial sag and tension are the same as before; the final conditions are:

$$S_f = 2.14 \text{ feet}$$

$$H_{\text{Steel}} = 1023 \text{ pounds}$$

$$H_{\text{Total}} = 393 \text{ pounds}$$

$$H_{\text{Shield}} = -435 \text{ pounds}$$

$$H_{\text{Diel}} = -82 \text{ pounds}$$

$$H_{\text{Cen}} = -113 \text{ pounds}$$

Notice that the cable is under compressive forces.

The force (F) required to cause the aluminum to buckle under compressive forces is:

$$F = \frac{\pi^2 EI}{X^2}$$

Where:

I = Moment of inertia

X = Unsupported distance

The moment of inertia, I, for 750 cable is approximately 0.005 inch^4 so the maximum unsupported distance that the cable can be exposed to without buckling is about 34 inches. Although the lashing wire spacing is much less than 34 inches, it is quite conceivable that, at the pole, the cable will be unsupported for over 34 inches and cable buckling is imminent.

Long Spans - Cable Movement and Expansion Loops

Consider a long span, approximately 200 feet of 750 cable, with 1.5 percent sag at 60°F. Suppose that the cable has expansion loops and the cable can move freely as the temperature changes. Consider then that the temperature changes from 50°F at night to 110°F during the day. What is the differential cable movement? This much temperature change is not unreasonable to assume since solar heating and radiative cooling can account for a 28°F temperature change on unjacketed cable even if the ambient temperature does not change.

60°F		50°F	110°F
L	=	200 feet	200 feet
S	=	2 feet	2.60 feet
H	=	748 pounds	575 pounds
L _C	=	200.053 33 feet	200.090 26 feet
L _{Cable}	=	200.026 33 feet	200.188 32 feet
		-0.021 35 feet	+0.098 06 feet
		-0.256 inches	+1.177 inches
1.43 Inches Total			

Expansion Loop Life

The life of an expansion loop can vary significantly depending on a number of factors: the surface finish of the aluminum, the type of loop, the depth of the loop, the size of the cable, the wall thickness of the aluminum outer conductor, whether it's jacketed or not, and the excursion distance per cycle. Without going into expansion loops to any great extent, the following expansion loop lives are typical of semiflexible cable with measured 6 inch depth and total 1 in excursion (i.e., +0.5 inch and -0.5 inch from the neutral point). The expansion loops in 0.500 inch were formed with a LEMCO G120 and the 1.000 inch with a G240.

Cycles to Outer Conductor Fracture (1 Inch Excursion)

Type	Unjacketed	Jacketed
0.500	29,900	51,800
0.750	18,000	22,500
1.000	8,000	17,900

The life of other cable sizes can be roughly approximated by interpolation. If each cycle is equivalent to one day, then the life of 0.750 inch jacketed cable would be about 49 years. Measurements show that as you double the excursion distance, the life of the loop drops by a factor for jacketed cables and by a factor of about 20 for unjacketed cables. The depth of the loop is extremely important. For a 0.500 inch unjacketed cable with a 3-1/2 inch depth instead of 6 inches, the aluminum fractures at 1,500 cycles instead of 29,900 cycles.

For the specific case given above where the loop is exposed to 1.4 inch excursions, the life of the 750 cable loop is about 8 years. Therefore, even with modest temperature changes, a single expansion loop may not be adequate for long spans.

Wind Gusting

Aside from length changes due to temperature changes, changes can also occur due to load changes. Although load changes due to ice build-up are infrequent, perhaps a few times a year, load changes due to wind can occur quite frequently especially if gusting is considered.

The frequency and amplitude distribution of wind gusting is complicated and can vary significantly from one region to the next. In general, gusting is far more severe in urban areas with buildings than in flat, level country. Although there is some good data available on wind gusting, the next example simplifies the frequency and amplitude distribution of gusting to a single data set.

Consider a 150 feet span of cable, one 500J and one 750J cable, suspended between supports with 1.5 percent sag at 60°F in a town with buildings. Consider next that the distribution of wind gusts for a one year period can be represented by 1000 gusts from 20 miles/hour to 60 miles/hour. The following table can be generated:

Wind Speed (miles per hour)	Wind Force (pounds per square foot)	Cable Length (feet)
0	0	150.090 0
20	1.024	150.092 7
60	9.216	150.182 7

So, the change in length that the expansion loop must accommodate is 1.08 inches. Assuming that there are 365 one inch temperature cycles per year and 1000 inch gust cycles per year, then the life of the loop will decrease by a factor of 0.27 as compared to its life due to temperature changes. For the 0.750 inch cable mentioned above, the life of the loop should be derated from about 49 years to about 13 years.

CONCLUSION

The basic sag and tension equations have been expanded to account for changes in temperature and load. Special configurations, such as tight lashing and "Figure 8" type cable with composite materials, were also addressed. The application of these equations can help the cable engineer respond to the local utility about maximum tension and proper clearance of aerial plant. The equations can also be applied to help understand various failure modes such as center conductor pullouts and premature expansion loop cracking.

ACKNOWLEDGEMENTS

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APPENDIX

Table 1.

CABLE PROPERTIES:

Unjacketed Trunk And Feeder

Type	Weight (pound/foot)	Diameter (inches)	E _r (pounds/square inch x 10 ⁶)	a _r (inches/inch °F x 10 ⁻⁶)	A _r (square inches)
412	0.058	0.412	2.79	13.3	0.133 3
500	0.078	0.500	2.44	13.5	0.196 4
625	0.121	0.625	2.42	13.5	0.306 8
750	0.171	0.750	2.37	13.5	0.441 8
875	0.225	0.875	2.26	13.5	0.601 3
1000	0.325	1.000	2.62	13.4	0.785 4

Jacketed Trunk And Feeder

Type	Weight (pounds/foot)	Diameter (inches)	E _r (pounds/square inch x 10 ⁶)	a _r (inches/inch °F x 10 ⁻⁶)	A _r (square inches)
412J	0.074	0.470	2.16	13.6	0.173 5
500J	0.098	0.560	1.95	13.7	0.246 3
625J	0.146	0.685	2.02	13.7	0.368 5
750J	0.206	0.820	1.99	13.7	0.528 1
875J	0.266	0.945	1.76	13.9	0.777 6
1000J	0.377	1.080	2.26	13.5	0.916 1
TX565	0.106	0.625	1.77	14.0	0.306 8
TX840	0.212	0.910	1.69	14.1	0.650 4
TX1160	0.430	1.250	1.92	13.9	1.228 2

Messengered Feeder (Figure 8)

Type	Weight (pounds/foot)	Diameter (inches)	E _r (pounds/ square inch x 10 ⁶)	a _r (inches/ inch °F x 10 ⁻⁶)	A _r (square inches)	MSGR OD (inches)
412JMS	0.121	0.830	2.87	11.1	0.220 7	0.109
500JMS	0.145	0.930	2.53	11.5	0.293 6	0.109
625JMS	0.252	1.120	3.13	10.9	0.427 2	0.186
TX565JMS	0.183	1.020	3.24	10.5	0.365 7	0.186

TABLE 1,
Continued

Drop Cable And Lashing Wire

Type	Weight (pounds/foot)	Diameter (inches)	E_r (pounds/ square inch $\times 10^6$)	a_r (inches/ inch $^{\circ}\text{F} \times 10^{-6}$)	A_r (square inches)	MSGROD (inches)
59 Quad						
Single	0.027	0.262	1.17	10.8	0.042 5	
Messengered	0.039	0.417	2.03	8.89	0.052 6	0.051
6 Quad						
Single	0.034	0.297	1.22	10.6	0.055 6	
Messengered	0.046	0.452	1.90	9.03	0.065 8	0.051
7 Quad						
Single	0.045	0.350	1.21	10.4	0.079 8	
Messengered	0.066	0.527	2.24	8.66	0.094 1	0.072
11 Quad						
Single	0.071	0.434	1.06	10.2	0.126 7	
Messengered 1	0.100	0.657	1.91	8.59	0.149 4	0.083
Messengered 2	0.096	0.658	2.60	8.44	0.153 2	0.109
Lashing	0.007	0.045	—	—	—	—

Note: The messenger used on the 412 and 500 cable is a solid 0.109 inch EHS steel wire, a stranded 0.1875 inch EHS steel wire is used on the 625 and TX565.

E_r , a_r and A_r are the resultant elastic moduli, expansion coefficients and areas respectively.

TABLE 2.

**Mechanical Properties Of
Selected Materials**

Material	Elastic Modulus (pounds/ square inch x 10 ⁶)	Expansion Coefficient (inches/ inch °F x 10 ⁻⁶)
Steel	28 - 30	7.2
Copper	16	9.2
Aluminum	10	12.7
Cu Clad Al (10% by Volume)	10.6	12.2
Cu Clad Steel (23% Cond)	24 - 27	7.2
Tape/Braid	4.2 - 6.3	11 - 13
Foam Dielectric (T-10)	0.042	78
Jacket Material		
LDPE	0.028	72
LLDPE	0.042	72
MDPE	0.063	83
HDPE	0.123	67
PVC	0.0011	40

TABLE 3.

**Properties of Selected
Messenger Wires And
EHS Steel Strands⁷**

Type	Stranding	Diameter (inches)	Weight (pounds/foot)	Area (square inches)	Break Strength x 1000 pounds
0.051	solid	0.051	0.007	0.002 043	0.200
0.072	solid	0.072	0.014	0.004 072	0.365
0.083	solid	0.083	0.018	0.005 411	0.485
0.109	solid	0.109	0.031	0.009 331	1.800
0.125	7 x 0.041	0.123	0.032	0.009 241	1.83
0.187 5	7 x 0.062	0.186	0.073	0.021 133	3.99
0.218 75	7 x 0.072	0.216	0.098	0.028 500	5.40
0.25	7 x 0.080	0.240	0.121	0.035 185	6.65
0.281 25	7 x 0.093	0.279	0.164	0.047 550	8.95
0.312 5	7 x 0.104	0.312	0.205	0.059 464	11.20
0.375	7 x 0.120	0.360	0.273	0.079 168	15.40
0.437 5	7 x 0.145	0.435	0.399	0.115 590	20.80
0.5	7 x 0.165	0.495	0.516	0.149 677	26.90

TABLE 4.

NESC Loading Table³

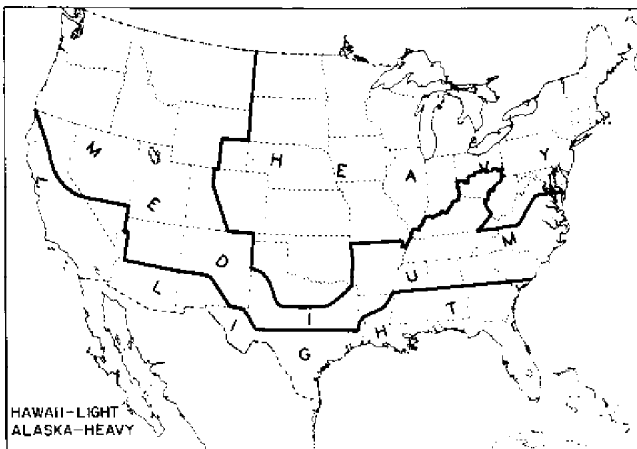
	Heavy	Medium	Light	Extreme Wind
Radial Ice (inches)	0.5	0.25	0.0	0.0
Wind (pounds/square foot)	4	4	9	See Fig. A2
Temperature (°F)	0	+ 15	+ 30	+ 60
Weight Adder (pounds/foot)	0.30	0.20	0.05	0.0

TABLE 5.

**NESC Clearance Requirements³
32°F, No Wind, With Ice,
Or At 120°F, No Wind**

Roads, alleys and other land subject to truck traffic or farm vehicles	15.5
Residential driveways, no truck traffic	15.5
Pedestrians only	14.0
Railroad crossings	23.5
Water areas sailboats prohibited (unless otherwise specified)	14.0

See the NESC for restrictions that apply.



◀ **Figure A1.**
NESC Loading District Map
(Printed With Permission)

Figure A2.
NESC Extreme Wind Loading Map ▶
(Printed With Permission)

